The Principles of Self Creation Cosmology and its Comparison with General Relativity

Garth A Barber

Kingswood Vicarage, Woodland Way, Tadworth, SURREY KT20 6NW, England.

Tel: +44 01737 832164   e-mail: garth.barber@virgin.net

Abstract

There are, at present, several gravitational and cosmological anomalies; the dark energy problem, the lambda problem, accelerating cosmological expansion, the anomalous Pioneer spacecraft acceleration, a spin-up of the Earth and an apparent variation of G observed from analysis of the evolution of planetary longitudes. These conundrums may be resolved in the theory of Self Creation Cosmology, in which the Principle of Mutual Interaction subsumes both Mach's Principle and the Local Conservation of Energy. The theory is conformally equivalent to General Relativity in vacuo with the consequence that predictions of the theory are identical with General Relativity in the standard solar system experiments. Other observable local and cosmological consequences offer an explanation for the anomalies above. The SCC universe expands linearly in its Einstein Frame and it is static in its Jordan Frame; hence, as there are no density, smoothness or horizon problems, there is no requirement for Inflation. The theory determines the total density parameter to be one third, and the cold dark matter density parameter to be two ninths, yet in the Jordan frame the universe is similar to Einstein's original static cylindrical model and spatially flat. Therefore there is no need for a 'Dark Energy' hypothesis. As the field equations determine the false vacuum energy density to be a specific, and feasibly small, value there is no 'Lambda Problem'. Finally certain observations in SCC would detect cosmic acceleration.

1 Introduction

1.1 A Possible Problem

This paper suggests that a series of disparate observations may now be raising questions about General Relativity (GR). The new theory of Self Creation Cosmology (SCC), (Barber, 2002), is presented as a viable alternative, against which GR can be theoretically and experimentally compared.

The cosmological problems, as widely reported in the literature, are as follows: Firstly, although the familiar density, smoothness and horizon problems of GR are at present resolved by Inflation, observations of galaxy clustering and gravitational lensing seem to indicate the density parameter to be only about a third of that required (Chae et al. 2002). Consequently the standard model demands the existence of unknown 'Dark Energy' to make up the missing mass (Chae et al. 2002). If some, or all, of this mass is false vacuum energy then, secondly, there is a 'Lambda Problem' in which the actual density of such energy is about 121 magnitudes smaller than theory predicts (Efstathiou, 1995). Finally, 'cosmological acceleration' (Perlmutter et al., 1999) has presented GR with a formidable problem, which is being resolved by such suggestions as that of dark energy or a dynamic cosmological constant $\Lambda(t)$. (e.g. Vishwakarma, 2002)

Closer to home the Pioneer spacecraft appear to have an anomalous sunward acceleration (Anderson et al. 2002a). There may be several explanations of this acceleration and it may have several components, however, as it has been observed a number of times, the excess over the General Relativity acceleration

$$a_P = (8.74 \ \pm \ 1.3) \text{ x } 10^{-8} \text{ cm/sec}^2$$

is equal to cH if $H = 87 \ km.sec^{-1}/Mpc$. Therefore it might be cosmological in nature.

A second anomaly as reviewed by Leslie Morrison and Richard Stephenson [(Morrison and Stephenson, 1998), (Stephenson, 2003)] arises from the analysis of the length of the day from ancient eclipse records. It is that in addition to the tidal contribution there is a long-term component acting to decrease the length of the day which equals

$$\triangle \text{ T/day/cy} = -6 \text{ x } 10^{-4} \text{ sec/day/cy.}$$

This component, which is consistent with recent measurements made by artificial satellites, is thought to result from the decrease of the Earths oblateness

following the last ice age. Although this explanation certainly merits careful consideration, and it is difficult to separate the various components of the Earth's rotation, it is remarkable that this value $\triangle$T/day/cy is equal to H if $H = 67$ $km.sec^{-1}/Mpc$. The question is why should this spinning up of the Earth's rotation have a natural time scale of the order of the age of the universe rather than the natural relaxation time of the Earths crust or the periodicity of the ice ages? This anomaly also may therefore be cosmological rather than geophysical in nature.

A third anomaly, which arises from the analysis of the residues of planetary longitudes, reveals that the Gravitational constant appears to be varying at a rate also of the order of Hubble's constant. An analysis [Krasinsky et al., (1985)] rendered a problematic value for a variation in G

$$\frac{\dot{G}}{G} \approx + (4 \pm 0.8) .10^{-11} yr^{-1}$$

with a caveat that the sign might be reversed. This value of $\frac{\dot{G}}{G}$ is equal to H if $H = 38$ $km.sec^{-1}/Mpc$, and therefore it too may be cosmological in nature.

If these are indeed three observations of Hubble's constant, then their values have a spread typical of other determinations of H with an average of $H = 64$ $km.sec^{-1}/Mpc$ in good agreement with more orthodox methods. Although there may well be other explanations for these anomalies it is remarkable that they all approximate Hubble's constant.

The question that arises, if these three observations are a signal for H, together with the cosmological problems mentioned above, is, "Notwithstanding the empirical success of GR, is there a problem with the theory?"

1.2 A Possible Solution

It was shown in the earlier paper (Barber, 2002) that SCC predicts identical outcomes as GR in the classical tests. Therefore the high precision tests, which have vindicated GR over many decades, do not falsify SCC either (Barber, 2003a). However two other falsifiable experiments have been proposed in principle (Barber, 2002), which are able to distinguish between the two theories. They ask the questions, "Do photons fall at the same rate as particles?" and "Is there a cut off for the Casimir force which approaches zero as space-time curvature approaches flatness?" Hence the theory is falsifiable. Furthermore there is another definitive test that is about to be performed

on the Gravity Probe B satellite. Whereas SCC predicts a 'frame-dragging' result equal to GR it predicts a geodetic precession of only 5/6,or 0.83 the GR value (Barber, 2003a). Apart from these tests of GR this paper will show that SCC offers solutions to the cosmological and local conundrums described above.

It will be seen that not only does the theory not suffer from a density, smoothness or horizon problem and therefore it does not require Inflation, but also the theory determines the universe's density to actually be a third of the critical density and therefore it does not require dark energy either. SCC determines the density of the false vacuum from its field equations to be a specific and feasibly small value, thus it also appears to resolve the 'Lambda Problem'. Finally observations of distant standard candles such as SN Ia would detect cosmic acceleration.

The theory actually predicts that the Pioneer spacecraft would appear to experience a sunward acceleration equal to cH because of a drift between atomic clock and ephemeris time. It also predicts rotating bodies should spin up at a rate equal to H. Finally it predicts $\frac{\dot{G}}{G}$ to be H but $\frac{(\dot{GM})}{GM}$ to be zero. Although a signal deduced from the evolution of orbital longitudes would detect the latter of these two, such a signal would also suffer the above clock drift. This would be interpreted as $\frac{\dot{G}}{G} = H$

It is here suggested that Self Creation Cosmology is a viable alternative to General Relativity.

1.3 The Principles of SCC

Einstein gave some consideration to two concepts, the local conservation of energy and Mach's Principle, which are not fully included in GR. At various times since the publication of Einstein's GR papers these concepts have been considered independently, in SCC they are considered together.

The first non-GR concept, the Local Conservation of Energy can be appreciated by considering the conservation of four-momentum, P^ν, of a projectile in free fall, which is a fundamental property of any metric theory such as GR as it necessarily follows from the equivalence principle. As a consequence the energy or 'relativistic mass' of a particle, (P^0), is not conserved, except when measured in a co-moving frame of reference, or in the Special Relativity (SR) limit. In any metric theory a particle's rest mass is necessarily invariant as it is mathematically identical to the norm of the four-momentum vector. This

requirement here defines the Einstein frame (EF). (Note: In the Brans and Dicke theory (BD) the EF is that conformal frame in which G is constant.) The local non-conservation of energy is a consequence of the fact that energy is not a manifestly covariant concept, that is its value is relative to the inertial frame of reference in which it is measured. As the equivalence principle does not allow a preferred frame, there is no definitive value for energy in any metric theory.

The second non-(fully)GR concept is Mach's Principle. This suggests that inertial frames of reference should be coupled to the distribution of mass and energy in the universe at large, hence one would actually expect there to be a preferred frame, that is a frame in which the universe as a whole might be said to be at rest, in which P^0 is conserved, in apparent contradiction to the spirit of the equivalence principle. In fact such a frame of reference does appear to exist, it is that in which the Cosmic Background Radiation (CBR) is globally isotropic.

These two problems are linked and resolved together in the new theory, SCC, by the proposal that energy is locally conserved when measured in a particular, preferred, frame of reference as selected by Mach's principle, that is the Center of Mass (CoM) of the system. It thus defines what is called the Jordan (energy) Frame [JF(E)] in which rest mass is required to include gravitational potential energy, as defined in that CoM frame of reference.

This local conservation of energy requires the energy expended in lifting an object against a gravitational field to be translated into an increase in rest mass. If $\Phi_N(x^\mu)$ is the dimensionless Newtonian gravitational potential defined by a measurement of acceleration in a local experiment in a frame of reference co-moving with the Centre of Mass frame (CoM),

$$\frac{d^2r}{dt^2} = -\nabla\Phi_N(r) \tag{1}$$

and normalized so that $\Phi_N(\infty) = 0$, then the local conservation of energy requires

$$\frac{1}{m_p(x^\mu)}\boldsymbol{\nabla} m_p(x^\mu) = \boldsymbol{\nabla}\Phi_N(x^\mu) \ , \tag{2}$$

where $m_p(x^\mu)$ is measured locally at x^μ. This has the solution

$$m_p(x^\mu) = m_0 \exp[\Phi_N(x^\mu)] \ , \tag{3}$$

$$\text{where} \qquad m_p r \to m_0 \qquad \text{as} \qquad r \to \infty \ .$$

The gravitational field equations of the new theory are modified to explicitly include Mach's principle, following BD, (Brans & Dicke, 1961), by including the energy-momentum tensor of a scalar field energy $T_{\phi\,\mu\nu}$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi}{\phi}\left[T_{M\mu\nu} + T_{\phi\,\mu\nu}\right] \ . \tag{4}$$

where $T_{M\mu\nu}$ is the energy momentum tensors describing the matter field. The scalar field $\phi \approx \frac{1}{G_N}$ is coupled to the large scale distribution of matter in motion, described by a field equation of the simplest general covariant form

$$\Box\phi = 4\pi T_M \ , \tag{5}$$

T_M is the trace, $(T_{M\,\sigma}^{\,\sigma})$, of the energy momentum tensor describing all non-gravitational and non-scalar field energy and where the Brans Dicke parameter λ has been determined to be unity. (Barber, 2002)

In SCC mass is created out of the gravitational and scalar fields according to the Principle of Mutual Interaction (PMI), in which the scalar field is a source for the matter-energy field if and only if the matter-energy field is a source for the scalar field.

$$\nabla_\mu T_{M\,\nu}^{;\,\mu} = f_\nu\left(\phi\right)\Box\phi = 4\pi f_\nu\left(\phi\right)T_M \ , \tag{6}$$

As a consequence photons still do traverse null-geodesics, at least *in vacuo,*

$$\nabla_\mu T_{em}^{\,\mu}{}_\nu = 4\pi f_\nu\left(\phi\right)T_{em} = 4\pi f_\nu\left(\phi\right)\left(3p_{em} - \rho_{em}\right) = 0 \tag{7}$$

where p_{em} and ρ_{em} are the pressure and density of an electromagnetic radiation field with an energy momentum tensor $T_{em\,\mu\nu}$ and where $p_{em} = \frac{1}{3}\rho_{em}$ and where it will be shown that

$$f_\nu\left(\phi\right) = \frac{1}{8\pi\phi}\nabla_\nu\phi \ . \tag{8}$$

2   The SCC Conformal Transformation

These SCC principles have the consequence (Barber, 2002) that in the Jordan Frame, in which energy is locally conserved in the Centre of Mass frame of reference, a photon has constant frequency and its energy is conserved even when crossing a gravitational field. Gravitational red shift is interpreted as a

gain of potential energy, and hence mass, of the measuring apparatus, rather than the loss of (potential) energy by the photon.

There are two questions to ask in order that a Weyl metric may be set up spanning extended space-time; "What is the invariant standard by which objects are to be measured?" and "How is that standard to be transmitted from event to event in order that the comparison can be made?" In GR and the SCC EF the principle of energy-momentum conservation, i.e. invariant rest mass, determines that standard of measurement to be fixed rulers and regular clocks. In the SCC JF(E), on the other hand, the principle of the local conservation of energy determines that standard of measurement to be a "standard photon", with its frequency (inverse) determining the standard of time and space measurement, and its energy determining the standard of mass, all defined in the CoM, Machian, frame of reference.

In this theory the EF is the natural frame in which to interpret experiments and observations of matter and the JF(E) is the natural frame in which to interpret astronomical and cosmological observations and gravitational orbits. The conformal transformation of a metric $g_{\mu\nu}$ into a physically equivalent alternative $\widetilde{g}_{\mu\nu}$ is described by

$$g_{\mu\nu} \to \widetilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \ . \tag{9}$$

The JF of SCC requires mass creation, ($\nabla_\mu T_{M\ \nu}^{\ \mu} \neq 0$), therefore the scalar field is non-minimally connected to matter. The JF Lagrangian density is,

$$L^{SCC}[g, \phi] = \frac{\sqrt{-g}}{16\pi} \left(\phi R - \frac{\omega}{\phi} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi \right) + L_{matter}^{SCC}[g, \phi] \ , \tag{10}$$

and its conformal dual, [Dicke (1962)], by a general transformation $\widetilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$, is

$$
\begin{aligned}
L^{SCC}[\widetilde{g}, \widetilde{\phi}] \ &= \ \frac{\sqrt{-\widetilde{g}}}{16\pi} \left[\widetilde{\phi} \widetilde{R} + 6\widetilde{\phi} \widetilde{\Box} \ln \Omega \right] + \widetilde{L}_{matter}^{SCC}[\widetilde{g}, \widetilde{\phi}] \\
&\quad - \frac{\sqrt{-\widetilde{g}}}{16\pi} \left[2\left(2\omega + 3\right) \frac{\widetilde{g}^{\mu\nu} \widetilde{\nabla}_\mu \Omega \widetilde{\nabla}_\nu \Omega}{\Omega^2} + 4\omega \frac{\widetilde{g}^{\mu\nu} \widetilde{\nabla}_\mu \Omega \widetilde{\nabla}_\nu \widetilde{\phi}}{\Omega} + \omega \frac{\widetilde{g}^{\mu\nu} \widetilde{\nabla}_\mu \widetilde{\phi} \widetilde{\nabla}_\nu \widetilde{\phi}}{\widetilde{\phi}} \right] \ .
\end{aligned}
\tag{11}
$$

Now mass is conformally transformed according to

$$m\left(x^\mu\right) = \Omega \widetilde{m}_0 \tag{12}$$

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[see Dicke, (1962)], where $m\left(x^{\mu}\right)$ is the mass of a fundamental particle in the JF and $\widetilde{m}_0$ its invariant mass in the EF. Therefore the local conservation of energy in the SCC JF, Equations 3 and 12, require

$$\Omega = \exp\left[\Phi_N\left(x^{\mu}\right)\right] . \tag{13}$$

The question is, "How does ϕ transform?" In the BD EF and the GR JF where gravitation and mass are inextricably combined, the conformal transformation of the scalar field depends on the dimensionless and therefore invariant,

$$Gm^2 = \widetilde{G}\widetilde{m}^2 \tag{14}$$

i.e. $\widetilde{\phi}_{BD} = \phi_{BD}\Omega^{-2}$.

Defining the conformal transformation Ω by

$$\Omega = (G\phi)^{\alpha} \tag{15}$$

then

$$\widetilde{\phi}_{BD} = G^{-2\alpha}\phi_{BD}^{(1-2\alpha)} , \tag{16}$$

which in the BD case, where $\widetilde{G}$ is constant, requires $\alpha = \frac{1}{2}$.

In SCC, however, it is postulated that potential energy should also be convoluted with gravitation and mass. This is achieved by including the conformal parameter, Ω, which is now an expression of potential energy, with the gravitational 'constant' and mass. The dimensionless conformal invariant now becomes

$$Gm^2\Omega^{\beta} = \widetilde{G}\widetilde{m}^2\widetilde{\Omega}^{\beta} . \tag{17}$$

Now $\widetilde{\Omega} = 1$ by definition therefore $G\widetilde{m}^2$ is invariant in that frame, and as $\widetilde{m}$ is constant, hence $\widetilde{G}$ and consequentially $\widetilde{\phi}$ are constant. In this case Equation 15 yields

$$\widetilde{\phi}_{SCC} = G^{-\alpha(2+\beta)}\phi_{SCC}^{[1-\alpha(2+\beta)]} , \tag{18}$$

which sets the following condition for the EF

$$\beta = \frac{1}{\alpha} - 2 . \tag{19}$$

If $\omega = -\frac{3}{2}$ and $\widetilde{\Box}\ln\Omega = 0$, then as $\widetilde{\phi}$ is constant, Equation 11 reduces to

$$L^{SCC}[\widetilde{g}] = \frac{\sqrt{-\widetilde{g}}}{16\pi G_N}\widetilde{R} + \widetilde{L}_{matter}^{SCC}[\widetilde{g}] , \tag{20}$$

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where matter is now minimally connected. Thus with these three conditions the conformal transformation of the Lagrangian density, Equation 10, reduces to canonical GR. The value $\omega = -\frac{3}{2}$ can either be set empirically (Barber, 2002) or determined from the first principles of the theory (Barber, 2003b). This unique frame is designated the Jordan energy Frame, [JF(E)] because in it energy is locally conserved. The last condition, $\widetilde{\Box} \ln \Omega = 0$, is the vacuum condition, $\widetilde{\Box} \widetilde{\Phi}_N (\widetilde{x}^{\mu}) = 0$, as this reduces to $\widetilde{\nabla}^2 \widetilde{\Phi}_N (\widetilde{x}^{\mu}) = 0$ in a harmonic coordinate system. The metrics thus relate in vacuo according to Equation 9

$$g_{\mu\nu} \to \widetilde{g}_{\mu\nu} = \exp\left[2\Phi_N\left(x^{\mu}\right)\right] g_{\mu\nu} \; , \tag{21}$$

where $\widetilde{g}_{\mu\nu}$ is the GR metric. As matter is minimally connected in the EF it is necessary first to carry out the variational principle in that frame and then conformally transform the result into the JF(E).

The energy-momentum tensor of matter is thereby defined in the EF by

$$\widetilde{T}^{SCC}_{M\mu\nu} = \frac{2}{\sqrt{-\widetilde{g}}} \frac{\partial}{\partial \widetilde{g}^{\mu\nu}} \left(\sqrt{-\widetilde{g}} \widetilde{L}^{SCC}_{matter} \right) \; . \tag{22}$$

The corresponding energy-momentum tensor of matter in the JF(E) is defined by the conformal dual of this definition in the EF,

$$\widetilde{T}^{SCC}_{M\,\mu\nu}\left(\widetilde{g}^{\mu\nu}\right) \to T^{SCC}_{M\,\mu\nu}\left(g^{\mu\nu}\right) \; , \text{ where } g^{\mu\nu} = \exp\left[2\Phi_N\left(x^{\mu}\right)\right]\widetilde{g}^{\mu\nu}. \tag{23}$$

The Lagrangian density in the EF is given by

$$L^{SCC}[\widetilde{g}, \widetilde{\phi}] = \frac{\sqrt{-\widetilde{g}}}{16\pi G_N} \widetilde{R} + \widetilde{L}^{SCC}_{matter}[\widetilde{g}] + \frac{3\sqrt{-\widetilde{g}}}{8\pi G_N} \widetilde{\Box}\widetilde{\Phi}_N\left(\widetilde{x}^{\mu}\right) \; . \tag{24}$$

Its conformal dual in the JF(E) is that of Equation 10 with $\omega = -\frac{3}{2}$,

$$L^{SCC}[g, \phi] = \frac{\sqrt{-g}}{16\pi} \left(\phi R + \frac{3}{2\phi} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi \right) + L^{SCC}_{matter}[g, \phi] \; , \tag{25}$$

and the corresponding field equation to this Lagrangian density is

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \;=\; \frac{8\pi}{\phi} T_{M\mu\nu} - \frac{3}{2\phi^2} \left(\nabla_\mu \phi \nabla_\nu \phi - \frac{1}{2} g_{\mu\nu} g^{\alpha\beta} \nabla_\alpha \phi \nabla_\beta \phi \right) \tag{26}$$
$$+ \frac{1}{\phi} \left(\nabla_\mu \nabla_\nu \phi - g_{\mu\nu} \Box \phi \right) \; .$$

The SCC EF Lagrangian is de-coupled from the scalar field. The novel feature of SCC, distinguishing it from simple JF GR, is that Mach's Principle is fully incorporated in the JF(E) by applying Equation 5. The relationship between the field equations, 5 and 26 is obtained by covariantly differentiating Equation 26. After multiplying through by ϕ ($\neq 0$), taking ∇_μ, using the Bianchi identities, Equation 5 and the identity

$$\nabla_\sigma \phi R^\sigma_\nu = \nabla_\nu \left(\Box \phi \right) - \Box \left(\nabla_\nu \phi \right) \ ,$$

one obtains the PMI expression:

$$\nabla_\mu T^\mu_{M\nu} = \frac{1}{8\pi} \frac{1}{\phi} \nabla_\nu \phi \Box \phi \ . \tag{27}$$

On using Equation 5 this becomes

$$\nabla_\mu T^\mu_{M\nu} = \frac{1}{2} \frac{1}{\phi} \nabla_\nu \phi T_M \ . \tag{28}$$

In this theory where the conformal invariant is $Gm^2\Omega^\beta$ the relationship between the scalar field in the JF(E) and EF is $\phi_{SCC} = \Omega^{(2+\beta)} \widetilde{\phi}_{SCC}$. The parameter β is determined by the principle of the conservation of energy. Furthermore when $\nabla_\mu \phi = 0$ Equation 28 reduces to

$$\nabla_\mu T^\mu_{M\nu} = 0 \tag{29}$$

and it was shown that in this immediate locality SCC reduces to SR. In that locality, where $g_{\mu\nu} \rightarrow \eta_{\mu\nu}$ and $\phi = $ constant, the theory admits a ground state solution.

The field equation can be cast in a form that does not contain the second derivatives of ϕ, which are necessarily convoluted with the gravitational terms of the affine connection. When cast into its 'corrected' form the left hand side of the gravitational field equation, the Einstein tensor $G_{\mu\nu}$, becomes the 'affine' Einstein tensor $^\gamma G_{\mu\nu}$ and in this case the whole JF(E) equation becomes

$$^\gamma G_{\mu\nu} = \frac{8\pi}{\phi} T_{M\mu\nu} + \frac{\left(\omega + \frac{3}{2}\right)}{\phi^2} \left(\nabla_\mu \phi \nabla_\nu \phi - \frac{1}{2} g_{\mu\nu} g^{\alpha\beta} \nabla_\alpha \phi \nabla_\beta \phi \right) \tag{30}$$

so in the SCC case, where $\omega = -\frac{3}{2}$, this reduces down to

$$^\gamma G_{\mu\nu} = \frac{8\pi}{\phi} T_{M\mu\nu} \ . \tag{31}$$

In this representation of the theory the gravitational field equation reduces to an original Self Creation cosmology (Barber, 1982) in which the scalar field is minimally coupled to the metric, and which only interacts with the material universe by determining the gravitational coefficient G. This original representation of the theory has been the subject of some discussion over the past twenty years, [Abdel-Rahman, (1992), Abdussattar & Vishwakarma, (1997), Barber, (2002), (2003a), (2003b), Brans, (1987), Maharaj, (1988), Mohanty & Mishra, (2002), Mohanty & Mishra & Biswal, (2002), Mohanty, Sahu & Panigrahi, (2002), Mohanty, Sahu & Panigrahi, (2003), Pimentel, (1985,) Pradhan & Pandey (2002), Pradhan & Vishwkarma (2002), Rahman & Abdel, (1993), Ram & Singh, (1998a), (1998b), Reddy, (1987a), (1987b), (1987c), (1987d), Reddy, Avadhanulu & Venkateswarlu, (1987), (1988), Reddy & Venkateswarlu,(1988), (1989), Sahu & Panigrahi, (2003), Sanyasiraju & Rao, (1992), Shanthi & Rao, (1991), Singh, Singh & Srivastava, (1987), Singh & Singh, (1984), Singh, (1986), (1989), Soleng, (1987a), (1987b), Venkateswarlu & Reddy, (1988), (1989a), (1989b), (1989c), (1990), Wolf, (1988)].

3 The Standard Formulae of SCC

3.1 The SCC Field Equations

The SCC Action Principle gives rise to the following set of equations:
The scalar field equation

$$\Box\phi = 4\pi T_M \ , \tag{32}$$

The gravitational field equation

$$
\begin{aligned}
R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R \ \ = \ \ & \frac{8\pi}{\phi}T_{M\mu\nu} - \frac{3}{2\phi^2}\left(\nabla_\mu\phi\nabla_\nu\phi - \frac{1}{2}g_{\mu\nu}g^{\alpha\beta}\nabla_\alpha\phi\nabla_\beta\phi\right) \\
& + \frac{1}{\phi}\left(\nabla_\mu\nabla_\nu\phi - g_{\mu\nu}\Box\phi\right) \ ,
\end{aligned} \tag{33}
$$

The creation equation, which replaces the conservation equation (Equation 29)

$$\nabla_\mu T_{M\ \nu}^{\mu} = \frac{1}{8\pi}\frac{1}{\phi}\nabla_\nu\phi\Box\phi \tag{34}$$

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These field equations are manifestly covariant, there is no preferred frame of reference or absolute time. However in order to solve them one has to adopt a specific coordinate system; the CoM of the system in the spherically symmetric One Body Case, or that of the comoving fluid of the cosmological solution. In those frames of reference there is a specific coordinate time as in the standard GR solutions. These JF(E) solutions of SCC, moreover, have the property not only of being in the Machian frame of reference but also of locally conserving mass-energy.

3.2 The Spherically Symmetric Solution

The Robertson parameters are

$$\alpha_r = 1 \qquad \beta_r = 1 \qquad \gamma_r = \frac{1}{3} \ , \tag{35}$$

and therefore the standard form of the Schwarzschild metric is

$$d\tau^2 = \left(1 - \frac{3G_N M}{r} + ..\right) dt^2 - \left(1 + \frac{G_N M}{r} + ..\right) dr^2 \tag{36}$$
$$-r^2 d\theta^2 - r^2 \sin^2 \theta d\varphi^2 \ .$$

The formula for ϕ is

$$\phi = G_N^{-1} \exp(-\Phi_N) \tag{37}$$

and that for m is, (Equation 3),

$$m_p(x_\mu) = m_0 \exp(\Phi_N).$$

Hence we note that in this case, in Equation 19, $\alpha = -1$ and $\beta = -3$, thus in the spherically symmetric solution to the field equations Equation 15 becomes

$$\Omega = (G\phi)^{-1} \ . \tag{38}$$

3.3 Local Consequences of the Theory

There are two Gravitational constants, G_N, which applies to particles and measurable in Cavendish type experiments as the standard Newtonian constant and G_m, which applies to photons and is that constant which determines the curvature of space-time. These two constants relate together according to

$$G_N = \frac{2}{3} G_m \ . \tag{39}$$

Hence, if normal Newtonian gravitational acceleration is g, the acceleration of a massive body caused by the curvature of space-time is $\frac{3}{2}g$ 'downward' compensated by an 'upward' acceleration caused by the scalar field of $\frac{1}{2}g$.

Finally in the JF(E) the radial inward acceleration of a freely falling body is given by the non-Newtonian expression

$$\frac{d^2r}{dt^2} = -\left\{1 - \frac{G_N M}{r} + ...\right\}\frac{G_N M}{r^2} \; . \tag{40}$$

In the earlier paper it was seen that the effect of this non-Newtonian perturbation was to compensate for the effect of the scalar field upon the curvature of space-time.

The acceleration experienced by a freely falling particle is given by

$$m_0\frac{d^2r}{dt^2} = -m(r)\frac{G_N M}{r^2} \; . \tag{41}$$

We see that m_0 can be thought of as 'inertial-mass', which measures inertia and $m(r)$ as 'gravitational mass', which interacts with the gravitational field with

$$\underset{r\to\infty}{Lim} \; m(r) = m_0 \; .$$

As described in the original paper, (Barber, 2002), the conformal equivalence between the JF(E) and the EF, which is canonical GR, results in the predictions in the standard tests being identical with GR. In the JF(E) it was seen in detail that the action of the non-conservation of the energy-momentum tensor for matter resulted in an extra 'scalar-field' force acting on particles which exactly compensated for the scalar field perturbation of the curvature of the space-time manifold. Nevertheless two definitive experiments were suggested which examine the interaction of the photon and the vacuum energy fields with ordinary matter.

4   The Cosmological Solution

4.1   Deriving the General Cosmological Equations

Using the Cosmological Principle the usual assumptions of homogeneity and isotropy can be made to obtain the cosmological solutions to the field equations.

The privileged CoM frame in which physical units may be defined for any epoch is now the "rest frame" for the universe as a whole. Presumably it should be identified physically with that frame in which the microwave background radiation is globally isotropic.

According to SCC, a gravitational field, i.e. the curvature of space-time, is to be described in the JF(E), whereas observations using atomic apparatus, based on an atomic clock, are referred to the EF. The two frames have to be transformed as appropriate.

There are four equations to consider. The first is the Gravitational Field Equation 33, which is exactly the same as the BD equation with $\omega = -\frac{3}{2}$ in the BD equation. The second is the Scalar Field Equation 5. In GR the third equation is the conservation equation which is replaced in SCC by the Creation Field Equation 27. The fourth equation is some equation of state, such as the dust filled universe $p = 0$, or the early radiation dominated universe in which $p = \frac{1}{3}\rho$. The SCC field equations demand an exotic equation of state.

The two gravitational cosmological equations are

$$\left(\frac{\dot{R}}{R}\right)^2 + \frac{k}{R^2} = +\frac{8\pi\rho}{3\phi} - \frac{\dot{\phi}\dot{R}}{\phi R} - \frac{1}{4}\left(\frac{\dot{\phi}}{\phi}\right)^2 , \tag{42}$$

$$\frac{\ddot{R}}{R} + \left(\frac{\dot{R}}{R}\right)^2 + \frac{k}{R^2} = -\frac{1}{6}\left(\frac{\ddot{\phi}}{\phi} + 3\frac{\dot{\phi}\dot{R}}{\phi R}\right) + \frac{1}{4}\left(\frac{\dot{\phi}}{\phi}\right)^2 . \tag{43}$$

The scalar cosmological equation

$$\ddot{\phi} + 3\frac{\dot{\phi}\dot{R}}{R} = 4\pi\left(\rho - 3p\right) . \tag{44}$$

The creation cosmological equation is

$$\dot{\rho} = -3\frac{\dot{R}}{R}\left(\rho + p\right) + \frac{1}{8\pi}\frac{\dot{\phi}}{\phi}\left(\ddot{\phi} + 3\frac{\dot{\phi}\dot{R}}{R}\right) . \tag{45}$$

(It is a moot point whether the scalar field ϕ is generated by the distribution of mass and energy via Equation 44, or whether mass is generated by the scalar field via Equation 45.)

Finally the equation of state remains

$$p = \sigma\rho , \tag{46}$$

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where $\sigma = +\frac{1}{3}$ in a radiation dominated universe and $\sigma = 0$ in a dust filled universe.

4.2 The SCC Cosmological Solution and Consequences

The five independent Equations, 42, 43, 44, 45 and 46 and the sixth relationship, provided by the conservation of a free photon's energy in the JF(E) together with Stephan's Law, provide a solution for the six unknowns $R(t)$, $\phi(t)$, $\rho(t)$, $p(t)$, k and σ. There are also the boundary conditions at $t = t_0$ (present epoch), R_0, ϕ_0, ρ_0, and p_0.

The cosmological 'self-creation equation' is found to be

$$\rho = \rho_0 \left(\frac{R}{R_0} \right)^{-3(1+\sigma)} \left(\frac{\phi}{\phi_0} \right)^{\frac{1}{2}(1-3\sigma)} , \tag{47}$$

which is the equivalent GR expression with the addition of the last factor representing cosmological 'self-creation'. However for a photon gas $\sigma = +\frac{1}{3}$ so Equation 47 reduces to its GR equivalent, consistent with the Principle of Mutual Interaction that there is no interaction between a photon and the scalar field,

$$\rho_{em} = \rho_{em\,0} \left(\frac{R}{R_0} \right)^{-4} . \tag{48}$$

Since $\rho_{em} \propto T_{em}^4$ where T_{em} is the Black Body temperature of the radiation, the GR relationship $T_{em} \propto R^{-1}$ still holds. Also as the wavelength λ_{em} of maximum intensity of the Black Body radiation is given by $\lambda_{em} \propto T_{em}^{-1}$, SCC JF(E) retains the GR relationship

$$\lambda_{em} \propto R . \tag{49}$$

However in the SCC JF(E) λ_{em} is constant for a free photon, even over curved space-time, and it is particle masses which vary. Therefore in the JF(E) Equation 49 becomes simply

$$R = R_0 . \tag{50}$$

In the Jordan energy frame the universe is static when measured by light, that is a co-expanding "light ruler" is unable to detect the expanding universe.

The cosmological gravitational and scalar field equations are solved to yield

$$(5 - 3\sigma)\frac{\ddot{\phi}}{\phi} = 3(1 - 3\sigma)\left(\frac{\dot{\phi}}{\phi}\right)^2 \tag{51}$$

which has the two possible solutions;

Case 1 when $\sigma \neq -\frac{1}{3}$

$$\phi = \phi_0 \left(\frac{t}{t_0}\right)^{-2}, \tag{52}$$

which corresponds to a universe empty of everything except the false vacuum.

The presence of any matter or electromagnetic energy in the universe forces the solution to assume Case 2 with

$$\sigma = -\frac{1}{3}. \tag{53}$$

In which case Equation 51 has been shown (Barber, 2002) to have the solution

$$\phi = \phi_0 \exp(H_0 t), \tag{54}$$

where H_0 is Hubble's 'constant' in the present epoch, defined by $t = 0$, and $\phi_0 = G_N^{-1}$. By definition G_N is the value measured in "Cavendish type" experiments in the present epoch. Note the theory admits a cosmological ground state solution, $g_{\mu\nu} \rightarrow \eta_{\mu\nu}$ and $\nabla_\mu\phi = 0$ only when $t \rightarrow -\infty$, that is at the "Big Bang" itself. Equations 44, 46, 50, 54 and 53 yield

$$\frac{8\pi\rho}{\phi_0} = H_0^2 \exp(H_0 t). \tag{55}$$

This can be written in the form

$$\rho = \rho_0 \exp(H_0 t) \tag{56}$$

$$\text{where } \rho_0 = \frac{H_0^2}{8\pi G_N}, \tag{57}$$

if now, as usual, the critical density is defined $\rho_c = \frac{3H_0^2}{8\pi G_N}$, then $\rho_0 = \frac{1}{3}\rho_c$. Hence the cosmological density parameter Ω_c

$$\Omega_c = \frac{1}{3}. \tag{58}$$

Therefore, in this theory there is no need for 'Dark Energy'. The cosmological density parameter Ω_c comprises of baryonic (plus any cold dark matter) and radiation (plus any hot dark matter) components together with that of false vacuum energy. As the total pressure is determined by the constraints of the cosmological equations Equation 53, together with Equation 56, the total cosmological pressure is given by

$$p = -\frac{1}{3}\rho_0 \exp\left(H_0 t\right) \ . \tag{59}$$

To explain this it is suggested that a component of the cosmological pressure and density is made up of false vacuum. That is there is a "remnant" vacuum energy made up of contributions of zero-point energy from every mode of every quantum field which would have a natural energy "cut-off" $E_{\max}$ which in the cosmological case is determined, and limited, by the solution to the cosmological equations. Let there be three species, baryons, electromagnetic radiation and false vacuum:

$$p_b + p_{em} + p_f = -\frac{1}{3}\left(\rho_b + \rho_{em} + \rho_f\right) \ , \tag{60}$$

and as in the present epoch $p_b \approx 0$, $\rho_{em} \approx 0$, $p_{em} \approx 0$, and $p_f = -\rho_f$ we are left with

$$\rho_b = 2\rho_f \ . \tag{61}$$

Therefore the density parameter for cold matter (visible and dark) is

$$\Omega_b = \frac{2}{9} \approx 0.22 \ . \tag{62}$$

the difference between Ω_c and Ω_b would be interpreted as the hot dark matter component of "missing mass" or, as this component has negative pressure and evolves with time, it might be presently identified with "quintessence" [Cruz, N. et al., (1998)], [Huey, G. et al., (1999)], [Zlatev, I. et al., (1999)]. As this component is determined by the field equations the 'lambda problem' may have been resolved.

Assuming baryon conservation in a static universe, the inertial mass of a fundamental particle must be given by

$$m_i = m_0 \exp\left(H_0 t\right) \ . \tag{63}$$

A GR expanding universe with constant atomic masses of invariant size is replaced in SCC by a static universe with increasing atomic masses of decreasing size, that is "shrinking rulers".

4.3   The Transformation Into the Einstein Frame (EF)

Measurements of curvature or the wavelength/energy of a photon are made in the JF(E), however the physics of atomic structures is naturally described in the EF. It is now necessary to transform the units used in the JF(E) into the system used in physical measurement using atomic apparatus, that is the EF. The two frames are conformally related by Equation 9, using Ω again as the parameter of conformal transformation,

$$g_{\mu\nu} \to \widetilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \ ,$$

where the interval is invariant under the transformation

$$d\tau^2 = -g_{\mu\nu}dx^\mu dx^\nu = -\widetilde{g}_{\mu\nu}d\widetilde{x}^\mu d\widetilde{x}^\nu \ . \tag{64}$$

Now mass transforms according to Equation 12

$$m\left(x^\mu\right) = \Omega\widetilde{m} \ ,$$

therefore Equation 63 requires in the cosmological solution to the field equations

$$\Omega = \exp\left(H_0 t\right) \ . \tag{65}$$

The comparison of Equation 56 with Equation 54 reveals that $\rho \propto \phi$. Note that although in the One Body Problem $m\left(r\right) \propto \phi\left(r\right)^{-1}$, cosmologically $m\left(t\right) \propto \phi\left(t\right)$. Hence from Equation 19, in the cosmological solution to the field equations, $\alpha = +1$ and $\beta = -1$ and Equation 15 becomes

$$\Omega = G\phi \ . \tag{66}$$

From which length and time transform, by integrating along spacelike and timelike paths respectively

$$\widetilde{L} = L_0 \exp\left(H_0 t\right) \tag{67}$$

$$\text{and } \triangle\widetilde{t} = \triangle t \exp\left(H_0 t\right) \ . \tag{68}$$

These transformations are consistent with using the Bohr/Schrödinger/Dirac models of an atom to measure length and time under mass transformation.

The two time scales relate to each other as follows

$$\widetilde{t} = \frac{1}{H_0}\exp\left(H_0 t\right) \qquad \text{and} \qquad t = \frac{1}{H_0}\ln\left(H_0\widetilde{t}\right) \ , \tag{69}$$

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where $\widetilde{t}$ is time measured from the "Big Bang" in the EF, and t is time measured from the present day in the JF(E).

Applying this transformation to the universe's scale factor in two steps, the first step yields

$$\widetilde{R} = R_0 \exp\left(H_0 t\right) \ . \tag{70}$$

This expression uses mixed frames, that is length is in the EF and time is in the JF(E).If we now substitute for t in Equation 70 we obtain the scale factor of the universe in the EF.

$$\widetilde{R} = R_0 \frac{\widetilde{t}}{\widetilde{t_0}} \ . \tag{71}$$

Thus when measured by physical rulers and clocks the universe is seen to expand linearly from a "Big Bang". The deceleration parameter

$$q = -\left(\frac{\ddot{\widetilde{R}}}{H^2 \widetilde{R}}\right) = 0 \ . \tag{72}$$

Therefore the horizon, smoothness and density problems of classical GR cosmology, which all arise from a positive, non zero q, do not feature in SCC. Hence it is unnecessary to invoke Inflation in this theory and indeed, with Equation 70, SCC might be considered to be a form of "Continuous Inflation".

The curvature constant k is given by Equations 43 and 42

$$\frac{k}{R_0^2} = +\frac{1}{12} H_0^2 \ , \tag{73}$$

so k is positive definite,

$$k = +1 \ , \tag{74}$$

that is the universe is finite and unbounded. From Equation 73 R_0 can be derived in terms of the Hubble time

$$R_0 = \sqrt{12} H_0^{-1} \ . \tag{75}$$

This may be seen by comparing Equation 42

$$\left(\frac{\dot{R}}{R}\right)^2 = +\frac{8\pi\rho}{3\phi} - \frac{k}{R^2} - \frac{\dot{\phi}\dot{R}}{\phi R} - \frac{1}{4}\left(\frac{\dot{\phi}}{\phi}\right)^2 \tag{76}$$

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with its general GR equivalent

$$\left(\frac{\dot{R}}{R}\right)^2 = +\frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \ . \tag{77}$$

Thus a GR interpretation of a SCC universe would yield a cosmological constant

$$\Lambda = -3\left[\frac{\dot{\phi}\dot{R}}{\phi R} + \frac{1}{4}\left(\frac{\dot{\phi}}{\phi}\right)^2\right] \ . \tag{78}$$

Now using the standard matter, curvature and cosmological constant density parameters,

$$\Omega_m = \frac{8\pi G_N \rho_0}{3H_0^2} \ , \ \Omega_k = -\frac{k}{R_0^2 H_0^2} \ \text{and} \ \Omega_\Lambda = \frac{\Lambda}{3H_0^2} \ , \tag{79}$$

and the SCC solutions given by Equations 57, 74, 50, 75 and 54 we obtain

$$\Omega_m = \frac{1}{3} \ , \ \Omega_k = -\frac{1}{12} \ \text{and} \ \Omega_\Lambda = -\frac{1}{4} \ , \ \text{i.e.} \ \Omega_m + \Omega_k + \Omega_\Lambda = 0 \ . \tag{80}$$

This explains the static universe in the JF(E) as in a GR analysis the energy contributions of matter, curvature and cosmological constant cancel out, in a similar way to the original static Einstein model. Furthermore it should be noted that the above value $\Omega_\Lambda = -\frac{1}{4}$ cannot be observed directly. At present, using a model based on GR, the total energy parameter is deduced from the observed spatial flatness to be unity. Therefore if the universe is as predicted by SCC so that $\Omega_m = +\frac{1}{3}$ then it would be thought that the density due to the cosmological constant is $\Omega_\Lambda = +\frac{2}{3}$, as indeed is the case.

4.4 Mixed-Frame Measurements

The frame in which a cosmological observation is made has to be carefully considered. Atomic measurements lend themselves to the EF, while remote observations receiving photons lend themselves to the JF(E). Some cosmological observations may be comparing two quantities each measured in either frame. For example, if the "expansion" of the universe is expressed comparing EF length and JF(E) time we obtain Equation 70

$$\widetilde{R} = R_0 \exp\left(H_0 t\right) \ .$$

Observations of distant supernovae compare the atomic theory of stellar evolution and supernova luminosity - an assessment made in the EF, with red shift, a geometric measurement made in the JF(E). In the SCC it is expected that such observations would detect a universe expanding exponentially according to Equation 70.

The mixed-frame expression for ϕ is given by Equations 69, and 54

$$\phi = \frac{1}{G_N} \frac{\widetilde{t}}{t_0} \backsim \widetilde{t} \ . \tag{81}$$

This might explain the Large Numbers Hypothesis (LNH) relationship $G \approx T^{-1}$ where G and T are the normal LNH dimensionless values of the gravitational "constant" and the age of the universe respectively.

By definition the mass of a fundamental particle in the EF, $\widetilde{m}$, is constant, although when measured by comparison with the JF(E) energy of a free photon, the mixed frame mass bears the same linear relationship

$$m\left(\widetilde{t}\right) = m_0 \frac{\widetilde{t}}{t_0} = m_0 \frac{\widetilde{R}}{R_0} \ , \tag{82}$$

which is normally interpreted in the EF as the free photon suffering a red shift

$$1 + z = \frac{R_0}{\widetilde{R}} \ . \tag{83}$$

Cosmological redshift in a static universe is interpreted as a measurement of the cosmological increase of the atomic masses of the measuring apparatus rather than by a 'doppler shift'. Also as a check, Equations 81 and 82 give the mixed frame variation of $\widetilde{\phi}$ as

$$\phi\left(\widetilde{t}\right) = \frac{1}{G_N} \frac{m}{m_0} \ , \tag{84}$$

$$\text{so} \qquad G\left(\widetilde{t}\right) m\left(\widetilde{t}\right) = G_N m_0 = \text{ a constant.}$$

This confirms that if atomic masses are the standard of mass and are thereby defined to be invariant in the EF, $\widetilde{\phi}$ and hence G are necessarily invariant also. Therefore whether G is observed to vary or not will depend on which frame is used to interpret the results. When measured in the EF, the gravitational field of a massive body remains invariant over cosmological time.

5   Conclusions

The theory explains the present quandary about the observed density of the universe and accelerating cosmological expansion. [Garnavich, P.M. et al., (1998)], [Filippenko, A.V. et al., (1998)], [Riess, A.G. et al., (1998)] There is no need to invoke a cosmological constant, dark energy and/or quintessence. There is, nevertheless, a requirement for dark matter of around $\Omega_{dm} = 0.2$ to explain galactic clustering. In the JF(E), appropriate for observations of photons, the universe is similar to the original Einstein static cylinder model. Hence it is spatially flat in agreement with observations of CMB anisotropies even though the total density parameter $\Omega_m = \frac{1}{3}$.

As GM is invariant, and because of the conformal equivalence between SCC and GR, gravitational orbits in the JF(E) are the same as in GR. However there is a secular variation in measuring space and time. The EF unit of time is that measured by atomic clocks, whereas the JF(E) unit of time is that determined by the frequency of a 'standard' photon and gravitational orbits, i.e. ephemeris time. In SCC the anomalous acceleration of the Pioneer spacecraft is explained as a clock shift between ephemeris time (JF(E) clock) and atomic clock time (EF clock). (Anderson et al., 2002a) (also see Ostermann 2002).

An analysis of the residuals of planetary longitudes rendered a value for a variation in G

$$\frac{\dot{G}(t)}{G(t)} \approx + \left(4 \pm 0.8\right).10^{-11} yr^{-1} \tag{85}$$

with a caveat that the sign might be reversed. [Krasinsky et al., (1985)] On the other hand, they also reported the contradictory null result [Hellings et al., (1983)] determined from accurate observations of the Viking Landers and the Mariner 9 spacecraft. This null result has been confirmed repeatedly since, recently by Anderson et al. and others (Anderson et al., 2002b), (Williams, 2001). The discrepancy between these two results might be explained by SCC, if a detailed analysis of these results accordingly to SCC is carried out in the future. The discrepancy may depend on whether $\frac{\dot{G}}{G}$ is being measured or $\frac{(\dot{GM})}{GM}$. As stated above GM is invariant in the theory. The null Viking result may be explained by the clock drift between ephemeris time and universal (atomic clock) time being compensated by a secular evolution of the spherically symmetric solution to the field equations.

Another observable effect arises in the JF(E) as a result of the variation

in $m(t)$. If angular momentum is conserved then $mr^2\omega$ is constant, but as atomic masses increase secularly, their radii will shrink.

$$\text{If } m(t) = m_0 \exp(H_0 t) \text{ (Equation 63),}$$

$$\text{then } r(t) = r_0 \exp(-H_0 t) \text{ (The inverse of Equation 70)}$$

$$\text{and if } \frac{d}{dt}\left(mr^2\omega\right) = 0 \ ,$$

$$\text{then } \frac{\dot{\omega}}{\omega} = -\left[\frac{\dot{m}}{m} + 2\frac{\dot{r}}{r}\right] = +H_0 \ , \tag{86}$$

and solid bodies such as the Earth should spin up when measured by JF(E), (ephemeris) time. It has indeed been reported that this spin up is observed. As mentioned above, the review by Leslie Morrison and Richard Stephenson [(Morrison and Stephenson 1998),(Stephenson 2003)], studying the analysis of the length of the day from ancient eclipse records reported that in addition to the tidal contribution there is a long-term component acting to decrease the length of the day which equals

$$\triangle \text{ T/day/cy} = -6 \text{ x } 10^{-4} \text{ sec/day/cy.}$$

This value, equivalent to $H = 67 \ km.sec^{-1}/Mpc$, is remarkably close to the best estimates of H_0. However at least part of this spin up is probably caused by a decrease of the Earth's moment of inertia.

How significant are these anomalies? Is their proximity to the value of H_0 merely coincidence, or is there new physics here? If it is new physics that is being observed then it is suggested here that SCC would be a candidate worth consideration. Either way the situation may be clarified by performing the definitive experiments described in principle in the earlier paper, (Barber, 2002) if it is not resolved earlier by the Gravity Probe B experiment.

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